Current Status of the EUV Engineering Test Stand


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The EUV Engineering Test Stand (ETS) has demonstrated the printing of static and scanned 100 nm dense features. This milestone was first achieved in 2001 with a developmental set of projection optics (PO Box 1) and with a low power LPP source (40W drive laser). Since that time, the source has been upgraded to a 1500W (3 chains, 500W per chain) TRW drive laser. Operating with one chain (500W), the printed static images for 100 nm features are comparable to those obtained with the low power source, while exposure time was decreased by a factor of 15 to 30. One hundred nanometer dense features printed in step-and-scan mode are of the same image quality as those obtained in static imaging. The stages have demonstrated combined x and y jitter values of 2 to 4 nm RMS over most of the wafer stage travel range, at the designed scanned speed of 10 mm/sices at the wafer. This value is less than half of the designed value and provides sufficient stability to support printing of 70 nm features. EUV specific sensors at the wafer and reticle planes have been demonstrated with the TRW laser and integration will be completed later this year. The developmental projection optics (PO Box 1) will be replaced later this year with an improved projection optics system (PO Box 2) capable of printing 70 nm dense features.

Keywords: EUVL, lithography, laser-produced-plasma, laser plasma source, maglev, magnetic levitation, stages, precision engineering, contamination

1. Introduction

Extreme Ultraviolet Lithography (EUVL) is now widely viewed by experts in the field as the leading candidate for next generation lithography for printing dense features down to 30 nm [1]. An alpha-class tool, called the EUV Engineering Test Stand (ETS), has been developed to demonstrate full-field printing of EUV images and to develop the required system learning for EUV commercialization [2]. Early last year, the ETS demonstrated full-field printing of 100 nm features in both static and step-and-scan mode using a low power (40W Nd:YAG) laser produced plasma (LPP) source [3-4]. Major upgrades to the source and stage subsystems have been completed since that time. The Xe cluster-jet target initially used has been reconfigured to use a Xe liquid spray jet target and the drive laser has been upgraded to a three-chain 1500 watt Nd:YAG laser developed by TRW. The stage system has been upgraded to incorporate a low thermal expansion wafer stage platen constructed of Zerodur™, and further modifications are in progress to incorporate a reticle changer to replace the fixed reticle currently installed in the ETS. Initial imaging results with the stage and source upgrades using one chain of the TRW laser are presented here. At the end of this year, the developmental projection system, PO Box 1, will be replaced with a projection system of the same design (PO Box 2) which has improved
figure and finish. Imaging experiments with PO Box 2 at the Advanced Light Source has demonstrated small-field imaging of 70 nm dense features and smaller.

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2. ETS Design Overview

The ETS is designed to provide alpha-class capabilities with extensive data gathering functionality to support early EUVL system learning. It is comprised of two major environmental enclosures; the source chamber which houses the laser-produced plasma (LPP) source and illumination system, and the main chamber which houses the projection optics and stage system (See Fig. 1).

The EUV radiation is generated by using a laser produced plasma having a target comprised of a dense spray of xenon particles. A pulsed Nd:YAG laser is focused through an in-vacuum lens, with a 250 mm focal length, onto the xenon jet target. EUV radiation from the source is collected by six C1 optics elements (known as the C1 condenser) surrounding the plasma. Each collector element focuses the EUV radiation into an arc-shaped field, which is rotated by a grazing-incidence C2 optics and a near-normal C3 optics to illuminate the well-corrected field of view of the projection system. A membrane type spectral-purity filter isolates the illuminator environment from the projection system environment and removes out-of-band radiation from the illuminating beam before it is incident on the reticle.

The main chamber houses the final condenser element, C4, which shapes the six channel illumination to cover the arc-shaped field of view; the reticle and wafer stages; and the projection optics system. The reticle stage is magnetically levitated and carries a reflecting six inch square mask. A linear motor drives the stage in the scanning direction while magnetic actuators provide for short travel in the remaining five degrees of motion. The reticle pattern is projected onto the wafer using a 4 mirror, 4x reduction optical system (PO Box) having a numerical aperture of 0.1. The PO Box is designed for printing full-field images in step-and-scan mode and is capable of 70 nm dense features at a k1 value of 0.52. The wafer stage is a magnetically levitated stage, similar in design to the reticle stage, but incorporates a mechanical lead-screw stage for long travel motions in the cross-scan direction as required to cover all sites on a 200 mm wafer. A system of capacitive sensors and laser gauges feeds back the actuator gaps and stage positions required for the feedback control system to execute stage movements and to maintain stage synchronization. The projection system and stage metrology is supported by an in-vacuum active vibration isolation system. The reticle and wafer platens are isolated from ground vibrations through feedback control. A robotic system is utilized to load and unload wafers without breaking vacuum in the main chamber.

The ETS operates in a vacuum environment to minimize EUV throughput losses due to gas absorption. In the source chamber, excess xenon from the LPP source flows into the chamber at a delivery pressure of ~ 3 MPa. Three 3200 l/s turbomolecular pumps remove the Xe from the chamber while maintaining an operational pressure of less than 0.7 Pa. A Xe recirculation system captures the exhausted Xe and recompresses the gas to the required delivery pressure. Filters are included in the recirculation system to purify the Xe gas before reintroduction into the gas jet nozzle. The recirculation system minimizes the
amount of Xe required for ETS operations, and limits the buildup of oxygen, nitrogen, water and/or hydrocarbons in the Illuminator. A residual gas analysis (RGA) system constantly monitors the operating environment.

The main chamber is designed to operate with three different environmental zones; the reticle, wafer, and optics zone. The three zones can be environmentally isolated from one another to minimize contamination of the projection optics from the reticle zone or the wafer zone. Turbomolecular pumps with a total pumping capacity of 5200 l/s are currently used. As in the source chamber, the optics zone utilizes an RGA system to continuously monitor the operating environment.

The ETS is supported by a number of subsystems. The environment is monitored and maintained in both vacuum chambers. Sensors are distributed throughout to measure pressure, EUV flux levels, temperatures, vibrations, the pupil fill profile, the aerial image characteristics, and a through-the-lens imager is used for tool setup. A control system performs continual monitoring of all subsystems and provides a flexible control for performing lithographic testing and environmental and source development experiments.

2.1. Illuminator Subsystem

A high powered source of EUV light is required by the ETS to achieve the desired EUV throughput. For the ETS, EUV radiation is produced in a laser-produced plasma (LPP) source which employs a Xe liquid spray target. A 250 mm focal length lens is located in the vacuum chamber to focus the laser energy onto the Xe jet. The expelled Xe gas is recirculated in a closed-looped system to minimize the amount of Xe required for ETS operations.

In the initial implementation, a cluster-jet target [5-6] based upon the supersonic expansion of gaseous Xe into a vacuum was used in conjunction with a 40W Coherent Infinity Nd:YAG laser. During the past year, the source has been upgraded to a 1500W TRW laser (replacing the 40W Coherent Infinity laser) and the Xe cluster jet has been replaced with a liquid Xe spray jet target. The major upgrade in drive laser power is progressing in stages using first one chain of the TRW laser and then progressing to all three chains. While both drive sources are Nd:YAG lasers, they differ in repetition rate and pulse characteristics. The Infinity laser operates at a maximum rate of 100 Hz, producing 400 mJ of infrared radiation with a pulse width of 4 ns. Each chain of the TRW laser operates at a rate of 1667 Hz, producing 300 mJ with a 10 ns pulse width. The chains can be operated singly at 1667 Hz, with two chains combined sequentially at 3335 Hz, with all three sequentially at 5000 Hz or with any number of chains synchronously at 1667 Hz.

At an operational nozzle-to-laser separation of 1.5 mm, the cluster jet source with the Infinity laser was found to produce adequate conversion efficiency for initial ETS system learning. To improve the conversion efficiency with the high powered laser, TRW developed a Xe liquid spray jet target using a 50 µm diameter orifice that produced stable EUV output for hours of operation with the laser operating at a stand-off distance of 2 mm [7].

The liquid spray jet system was modified to make it compatible with ETS space constraints, fabricated and installed in the ETS (See Fig. 2). Xenon gas at a pressure of 2-4 MPa is liquefied in a heat exchanger cooled by liquid nitrogen located immediately upstream of the 50 µm diameter orifice. The heat exchanger controls the temperature of the liquid xenon to an accuracy of ±1%. Operating at a plasma-to-nozzle separation of 4 mm, the stability of the source [8] has been adequate for initial lithographic testing with one TRW laser chain. The source is routinely operated for several hours without any significant degradation of the EUV output.

![Fig. 2. ETS liquid spray jet source showing the heat exchanger and collimator.](image-url)
2.2. Environmental Subsystem

The first environmental data taken from the ETS last year showed excellent control of high mass (>44 AMU) hydrocarbons in both the Main Chamber and Illuminator environments [9]. During the past year, environmental data has been continually collected for both the main chamber and the Illuminator. RGA data shows that the ETS main chamber and illuminator continue to be clean with high mass (>44 AMU) hydrocarbons well below the ETS specification of $1 \times 10^{10}$ torr (See Fig. 3 and 4). This control is the result of extensive outgas testing of all components and materials for detectable ($>10^{-12}$ Torr) species above mass 44, as measured by a residual gas analyzer (RGA). Materials or components showing measurable outgassing rates above mass 44 are rejected. To date, nearly 300 items have been outgas tested. Furthermore, the ETS was built with vacuum compatible designs, careful cleaning of parts, pre-baking of cabling and sub-assemblies where possible, and adherence to clean assembly procedures.

With the introduction of the high powered source, the C3 optics assembly originally installed in the ETS was replaced with a water-cooled version. The C3 optics assembly is a set of six individual optics residing in the source chamber and receives the highest EUV intensity of any optics in the ETS due primarily to the small EUV footprint at this optic. The C3’s view out-of-band ionizing radiation but do not view the plasma directly.

The first set of C3 optics removed from the ETS Illuminator were exposed to approximately 50 million laser pulses (20 months) of low power operation, and was extensively characterized using Auger spectroscopy and EUV reflectance measurements [10]. EUV reflectivity data on a typical sample indicated a decrease in reflectivity over the entire optical surface from an initial reflectivity of 66%. The measured reflectance varied from 48% in areas where EUV flux was the highest to 56% in areas without EUV but with considerable out-of-band ionizing radiation. Measurements of the reflectivity centroid wavelength show no significant change, suggesting the observed variations were due to surface contamination and not bulk multilayer damage. Auger electron spectroscopy indicates the contamination consisted almost entirely of carbon, with thicknesses ranging from 200 to 300 angstroms depending on location. No evidence of optics oxidation was found, indicating that EtOH successfully prevented EUV/H$_2$O oxidation of the outermost Si layer during exposure to both EUV and out-of-band radiation.

The carbon contamination on the C3 optic was removed by RF-O$_2$ cleaning. After cleaning, the reflectance was improved to approximately 63%, with a uniformity of 0.5%. Auger analysis showed that all the carbon was removed but that the cleaning process had exceeded the endpoint, producing an added 15 angstroms of silicon oxide on the surface. This added oxide accounted for the 3% post-cleaning loss in reflectance. To study the condition of the C1 condenser, witness samples are currently in place at various locations at the C1 plane.
2.3. Stage Subsystem

The magnetically levitated stage system has been operating in the ETS for the past year. Both the wafer stage and the reticle stage have performed to specifications needed for initial lithographic experiments using the low powered source and one chain of the high powered source. Evolving performance requirements, high-power source integration, and desired stage system reliability improvements have led to continual stage system upgrades.

The wafer and reticle stage subsystem consists of magnetically levitated stages (See Fig. 5 and 6), metrology for each stage, and control electronics. A feedback control system provides synchronization of the reticle and wafer stages during exposures. Throughput, structural stability, critical dimension, and wafer exposure characteristics determine stage subsystem limits for acceleration, scan speed, settle time, and dynamic stability. The ETS requires each stage to operate with a combined jitter of less than 7 nm (RMS) as referenced to the PO Box. The Z (focus) error must be less than 75 nm (mean+3 sigma). These specifications must be maintained during scanning of the wafer at 10 mm/s. Performance of 3 to 4 nm X, Y jitter and 50 nm focus error has been demonstrated in the ETS.

2.3.1. Stage subsystem upgrades

Lithographic results previously reported [2,11] included both static imaging and slow scanning (~10 µm/s at the wafer) imaging for 100 nm features. At that time, the stages met these requirements over a limited travel range. The effort over the last year has included mechanical and systematic improvements to meet full ETS performance requirements. The improvements have facilitated performance consistent with 70 nm feature imaging using the ETS high power source.

![Fig. 5. Wafer stage, shown with electrostatic chuck.](image)

![Fig. 6. Reticle stage, shown inverted with support structure.](image)

![Fig. 7. Jitter and focus error of site 1 at the center of the wafer.](image)
2.4. Projection Subsystem

The ETS projection optics system is a four-mirror ring-field design with a numerical aperture of 0.1 and an image reduction of 4X. The four mirrors are Zerodur substrates with 40 bi-layer pairs of Mo/Si deposited on the surface followed by a Si capping layer.

The developmental set of projection optics (Optics Set 1) is currently installed in the ETS and will be replaced later this year with Optics Set 2. The Set 2 optics is of the same design as Set 1 but is of higher optical quality and will enable the ETS to operate at the designed-to specifications. With the exception of high frequency roughness (spatial periods smaller than 1 micron), almost a factor of two improvement in the figure and surface finish of the Set 2 optical surfaces was achieved as compared with the Set 1 optics [2]. The improvement in optics quality results in an optical system with lower wavefront aberration and much reduced flare, both of which leads to improved lithographic performance.

2.4.1. PO Box 2 characterization

Fabrication, assembly, and alignment of PO Box 2 have been completed. To acquire early learning in high resolution imaging in parallel with ongoing system characterization of the ETS using PO Box 1, the Sub-field Exposure Station (SES) was developed at the Advanced Light Source. Operating in conjunction with a new illuminator design, partially coherent illumination that mimics the fill profile of the ETS 6 channel system as well as other profiles can be provided.

PO Box 2 was installed in the SES, and test patterns of sub-100 nm features have been printed using various pupil fill profiles [12]. Examples of 70 nm and 80 nm dense elbows using the ETS fill profile are shown in Figs. 8 and 9. The resolution is significantly improved when compared to the 100 nm dense features printed using PO Box 1 in the ETS [2]. The image quality at 70 nm is at least as high as that of 100 nm features printed using PO Box 1. In particular, the iso-dense bias is less apparent in the PO Box 2 images (70 nm) than in the PO Box 1 images (100 nm) printed in the ETS as shown in section 3. Further details regarding the characterization of PO Box 2 can be found in [12].

2.5. Sensors subsystem

The ETS is extensively equipped with sensors to collect data in support of system learning. It contains a variety of EUV-specific sensors in addition to vacuum monitors, temperature sensors, vibration monitors, residual gas monitors, etc. These sensors include wavelength filtered photodiodes nested within the first condenser element (C1) to monitor source output, EUV CCD cameras to monitor the source size and position, an EUV photo-emission sensor to monitor the signal from the final condenser element (C4), a Through-the-Lens Imager (TTLI), an aperture viewing system, dose/illumination distribution sensors at the reticle and wafer planes, and an aerial image monitor (AIM) at the wafer plane. The latter three have become operational during the past year.

2.5.1. Through-the-Lens Imaging (TTLI) system

The TTLI is used to verify system alignment, to locate features on the reticle, and to perform coarse alignment between the reticle and the wafer (See Fig. 10).
A mercury lamp source operating in conjunction with a folding mirror injects light into the EUV path directly upstream of the C4 mirror. Following the EUV path, the visible light beam reflects off the reticle and the PO Box and casts an image of the reticle onto the wafer. Light reflecting off the wafer is intercepted by a scraper mirror and is directed to the TTLI imaging lens, which then casts the superimposed image of the reticle and wafer through an optical port to an external video camera.

2.5.2. Aperture Viewing System

An aperture viewing system provides images of the EUV fill profile at the pupil of the PO Box. This diagnostic is used to characterize the fill profile and to perform final alignment of the illuminator. The pupil image is obtained by using an in-vacuum actuator to insert a scintillating screen into the EUV path just above the M3 mirror of the PO Box. EUV radiation falling on the scintillating screen produces a visible-light image that is viewed through a mirror, located above the scintillating screen and to the side of the EUV path. The image is acquired using a video camera, which views the scintillating screen through an optical port in the main chamber. The resultant image is shown in Figure 11.

2.5.3. Reticle flux sensor/reticle illumination monitor

There are two sensors at the reticle plane to measure EUV levels. The first is the reticle flux sensor which is located near the edge of the EUV smile profile. The main purpose of this sensor is to provide an in-situ measure of EUV flux at the reticle plane. This sensor was recently installed and characterization is underway.

The second sensor is the reticle illumination monitor (RIM). The primary function of this sensor is to measure the distribution of the EUV illumination at the reticle plane. A single detector is not feasible because the reticle stage does not include significant travel in the non-scan direction. As a result, this sensor is designed as a linear array of photodiode elements positioned on the reticle stage adjacent to the reticle (See Fig. 12). As the reticle stage scans across the EUV ring field, the illumination pattern is mapped out.

The sensor consists of four segments, each containing 20 photodiodes, placed side-by-side creating an 80 element array. The array is positioned behind 100 µm pinholes that precisely define the active regions. On-stage electronics amplify, digitize, and process the signals from the individual elements to eliminate noise pick-up and simplify cabling to the on-stage components.

2.5.4. Wafer dose sensor (WDS) and AIM sensor

At the wafer level, a single element sensor is used to measure the absolute pulse energy delivered at the wafer. The sensor is located near one corner of the wafer stage and is positioned behind a 50 µm pinhole to provide a well defined
detection area (See Fig. 13). Similar to the reticle illumination monitor, on-stage electronics amplify, digitize, and process the sensor signals.

Nested next to the wafer dose sensor is the Aerial Image Monitor (AIM). In the AIM sensor, a patterned structure, or AIM artifact, consisting of 100 nm wide slits etched on an EUV transparent membrane is placed in front of the detector assembly. The slits are 100 µm long and replicated 10 times to increase the collection area and the resulting signal strength. In operation, the AIM sensor scans across a periodic pattern in the aerial image that has the same pitch (10 µm) as the AIM artifact. The AIM sensor can be used to determine focus, monitor focus stability, measure drift or jitter between the EUV image and the stage, determine scan magnification and skew, and study image distortion. The AIM assembly shares many of the electronics with the wafer dose sensor. Examples of representative AIM data can be found in [15].

3. High Power Imaging Results

Static and scanned printed images of features down to 90 nm with the ETS using the high-power source (500W laser, 1 chain) and upgraded stage system has been demonstrated [15,16]. The initial high-power tests utilized a conservative source configuration to reduce environmental risk to the Cl condenser. In this configuration, a 50 µm orifice was used to provide a more stable and reliable source. In the future, a smaller orifice (30 µm) will be used to reduce the ambient gas pressure. The plasma-to-collimator exit distance was set to 4 mm to minimize environmental risk to the Cl condenser. Ongoing source work is underway to increase the EUV throughput while maintaining a high degree of source stability. The initial configuration provided an EUV output 15-to-30 times greater than with low power operation. The EUV dose stability was about 5% peak-to-peak during most of the lithographic exposures. A scanned 90 nm image of 45 degree elbows is shown in Fig. 14.

Figure 14: ETS scanned images of 45° elbows at 90 nm feature sizes.

Comparison of scanned and static images of 100 nm features printed with the ETS show near indistinguishable results (Fig. 15, 16).

4. Summary

The ETS has been extensively upgraded since the initial demonstration of static and scanned imaging early last year. The Xe jet system was upgraded to a Xe spray jet target and the low-power drive laser was replaced with a 1500W high power drive laser by TRW. To date, lithographic printing is routinely performed with one chain (500W) of the TRW laser. In addition, major stage upgrades have been completed that resulted in performance over two times better than the 7 nm RMS jitter specification required for 70 nm imaging. In the current configuration, dense features down to 90 nm have been printed in step-and-scan mode with quality comparable to static images. The Set 2 optics (PO Box 2) has demonstrated a substantial improvement in imaging quality when compared to PO Box 1 currently installed in the ETS. 70 nm features with PO Box 2 are comparable with 100 nm features with PO Box 1. The ETS will be upgraded with PO Box 2 in the coming year.

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